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Scintillation of a Radio Star at a Subauroral Latitude

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Scintillations of the radio source Cassiopeia A observed at 113 Mc/s during the period October 1961 through July 1964 were scaled to determine a semi-quantitative index of the scintillation of source power. For fixed values of local magnetic activity mean diurnal variations were established which peaked about two hours before solar and magnetic midnight. Mean sidereal variation peaked at lower transit; this effect, attributed primarily to latitude, is compared to satellite scintillations. Both diurnal and sidereal variations showed an increase of mean scintillation activity with increase of magnetic index. Detailed examination of low magnetic index periods showed that daytime scintillations were slightly higher on the western side (towards the magnetic pole), while nighttime scintillations showed symmetry. However, with increasing magnetic activity, scintillation indices are considerably higher at night in the west while daytime scintillations are skewed to the east. A comparison of these observations with Penndorf's model of traveling and permanent maxima of spread F is attempted. The general features of the diurnal-latitude variation of the radio star scintillation index is compared to the diurnal and latitude variation of spread F (topside and bottomside). While there is a general correlation, differences between scintillations and spread F noted in topside sounders are considerable.

1. Introduction

A series of measurements of the amplitude scintillations of the galactic radio source Cassiopeia A taken at the Sagamore Hill Radio Observatory have been analyzed for the period from October 1961 to July 1964. Previous other long term studies, such as the early work of Little and Maxwell [1952] and the analysis of a complete solar cycle by Briggs [1964], have established the main features of the scintillation behavior. In the present study an attempt at a more quantitative index of scintillation amplitude has encouraged a finer separation of the variables believed to govern the scintillation behavior.

Sagamore Hill Radio Observatory is located at Hamilton, Mass. Some of the geometrical factors pertinent to the observation of Cassiopeia A are outlined in figure 1. Current measurements made here with spaced receivers which simultaneously record passages of the beacon satellite, S-66, indicate that the height distribution of the irregularities producing ionospheric scintillations is generally centered between 200 and 600 km [Kidd, private communication]. The use of a 400 km subionospheric locus for the track of Cassiopeia A through the irregularities is, therefore, illustrative. Using it, the ray path at lower transit, 11° elevation, intersects regions of particle precipitation at a value of McIlwain's parameter [1961] $L=6.7$. This is near the southern edge of the region of maximum auroral activity. At upper transit, 74° elevation, the ray path intersects near $L=3.5$. The subionospheric locus is symmetric for the geomagnetic field since geomagnetic north is quite nearly geographic north at this site. On the other hand, the locus is quite skewed with respect to the local magnetic field lines since the magnetic declination near Hamilton is about 16° W and analysis of survey charts indicates

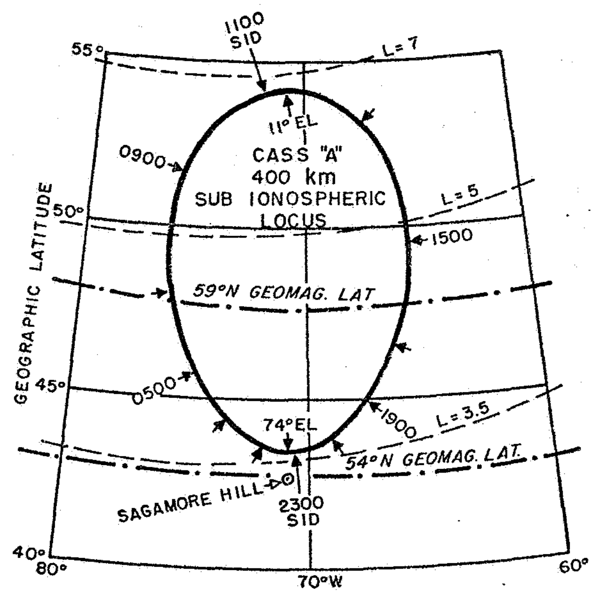

FIGURE 1. *Sagamore Hill Radio Observatory, Hamilton, Mass., 400 km subionospheric locus of ray path to Cassiopeia A.*
Local magnetic declination is 16° W. L values dip to the west.

that it holds this general direction over most of th 400 km illustration.

2. Observations

A multifrequency feed on the 84-ft radio telescop permitted simultaneous measurements at 63, 113, an 228 Mc/s. Receiver bandwidths varied from 100 t 300 kc/s; post detection time constants of 1 sec wer standard. The observational program consisted

·egularly scheduled periods of at least 48 hr during vhich Cassiopeia A and Cygnus A were tracked on ılternate half hours. In addition, Cassiopeia A was racked continuously when Cygnus A was below the ıorizon and during periods when the 84 foot antenna vas not on other schedules. For this paper, attention s restricted primarily to 113 Mc/s. Examination of he simultaneous records indicated that 63 Mc/s often ıad strong scattering effects during magnetic disturb-ınces. Observations of 228 Mc/s had low scintilla-ion index, and, consequently, higher relative errors, luring nondisturbed periods. The observations of 13 Mc/s, then, represent a compromise.

3. Data Reduction

A scintillation index was manually scaled from ›aper chart records which were very nearly linear in eceived power. Fixed reference sky positions were racked for 5 min as part of the antenna motion be-ween sources. A general confidence as to the amount f interference entering the radiometer system through ntenna sidelobes could be established at that time. 'he average source power was determined with respect ɔ the reference background. Representative power uctuations were determined by the third peak down :om the highest and the third peak up from the lowest ɔr a period of 5 to 10 min during the approximately 5 min on each source. The resultant scintillation ıdex

$$S=\frac{P(\text{third peak up})-P(\text{third peak down})\times 100}{2P(\text{average})}$$

'hile entirely arbitrary, was reproducible for different :aling personnel.

While there are conflicting interpretations of the ehavior of radio star scintillation under varying mag-etic activity [Moorcroft and Forsyth, 1963], recent bservations of satellite scintillation [Aarons, Mullen, ıd Basu, 1964], support statistical correlation of scin-llation and magnetic activity. As a first step in ttempting to isolate the variables, we have, therefore, ₃parated the Cassiopeia observations using the redericksburg (Va.) 3-hr index of magnetic activ-y, K_{Fr}.

The sidereal time (SID) at which a radio source has specific angle of elevation and azimuth is fixed by ›ometry. For example, at Sagamore Hill lower ansit of Cassiopeia A (11° elevation, directly north) :curs at 1121 SID. Due to the seasonal rotation of ıe earth about the sun, however, the local standard me (EST) for each fixed sidereal position decreases hr per month. Therefore, diurnal and sidereal fects are combined in any single measurement. 'hile a series of observations at a fixed local time will ıow spatial variation and a second series at a fixed dereal time will show diurnal variation, both will clude seasonal effects. As an example, Cassiopeia A only overhead at local midnight during the fall ıroral period each year. To assess the role of each ırameter, it is, therefore, usual to assume that the others can be normalized by averaging over yearly cycles. This is equivalent to assuming that the variables are independent. This assumption was adopted as a preliminary hypothesis.

4. Results

For this study, the 3590 observations, each representing a half hr sample, were grouped into statistical samples of 4 hr EST and 2 hr SID duration. In figure 2, we show smooth contours interpolated from sample means computed for periods of low K index (0 and 1). The contour grid is EST versus SID, seasonal effects would appear as a tendency for the contours to stretch diagonally along lines of constant season.

Assuming the possibility of normalization by averaging over a yearly cycle, the diurnal variation shown to the left of the isopleth was obtained by assigning equal statistical weight to the (unsmoothed) sample means. The maximum is found between 1900 and 2300. Note that local geomagnetic midnight is quite nearly local solar midnight at this observatory. The sidereal position variation was obtained similarly and is shown above the isopleth. The peak is at the most northern excursion, when the elevation is also lowest.

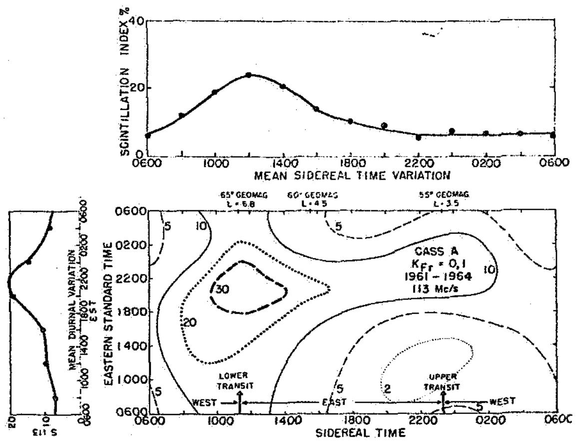

FIGURE 2. *Smoothed isopleths of 113 Mc/s scintillation index for quiet magnetic conditions.*

Averages over the yearly cycle produce diurnal (curve to the left) and sidereal (top) variations. Peak index was observed at 2100 EST near lower transit. The sharpest gradient in index occurred near 1800 EST consistent with observations with the satellite Transit 4A. Minimum gradients with low indices observed throughout were recorded between 0200 and 0400. There is a western enhancement of the index during daylight hours.

In figures 3, 4, and 5, we show smoothed isopleths for increased magnetic activity; $K_{Fr}=2$, 3, and ≥ 4 respectively. These display a similar change in scintillation index as a function of local time and sidereal position. The statistical increase of scintillation index with increase of magnetic activity is strikingly apparent when the isopleths are compared as in figure 6 where we have overlaid the 20 percent contours for each of the previous isopleths.

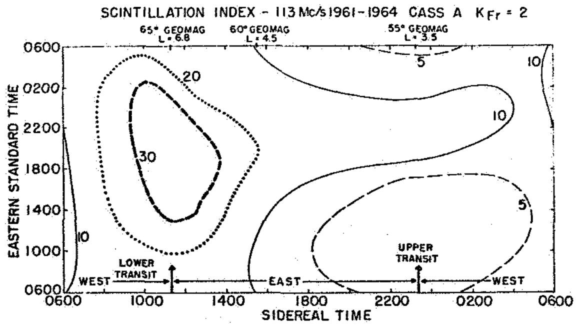

FIGURE 3. *Smoothed isopleths of 113 Mc/s scintillation index for K=2.*
Contours are nearly symmetric about lower transit.

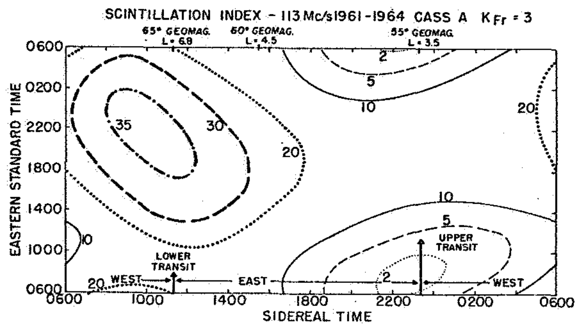

FIGURE 4. *Smoothed isopleths of 113 Mc/s scintillation index for K=3.*
With increasing K index contours move southwards away from the auroral zone (lower transit). Near lower transit there is enhancement of scintillation on the eastern portion during the day and in the west during the night.

5. Discussion

There are several features of the data which are apparent from the isopleths. The general features of the diurnal variation have been well established in the literature but there has been no satisfactory explanation for the cause of this variation, nor do we advance one, merely a relation to the diurnal variation of spread F. For the sidereal variation and the east-west asymmetry, it is now possible to interpret our results.

5.1. Sidereal Variation

The sidereal variation has been the source of considerable speculation since it was long considered to be primarily an elevation angle effect. This was strengthened by the lack of one to one correlation of scintillations with observed auroral activity and conflicting observations of correlation with either magnetic activity or with spread F. In recent years, observations of VHF signals from beacon satellites have clearly established a strong latitude dependence for the irregularities causing ionospheric scintillation.

As an example, we present a previously published illustration (fig. 7), [Joint Satellite Studies Group, 1965] which demonstrates the sharp increase of scintillation

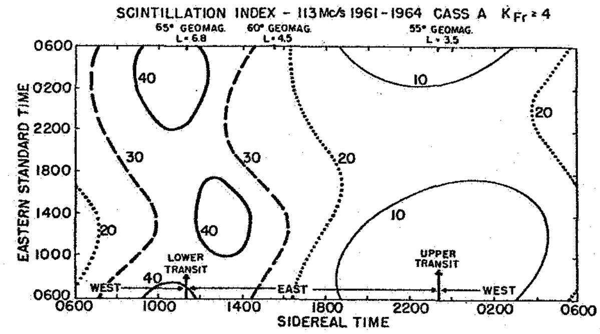

FIGURE 5. *Smoothed isopleths of 113 Mc/s scintillation index for K ≥ 4.*
For storm magnetic indices the diurnal peak has shifted to early morning hours. The east-west asymmetry has increased to the extent that there is a clear eastern enhancement near midday and a western enhancement at night.

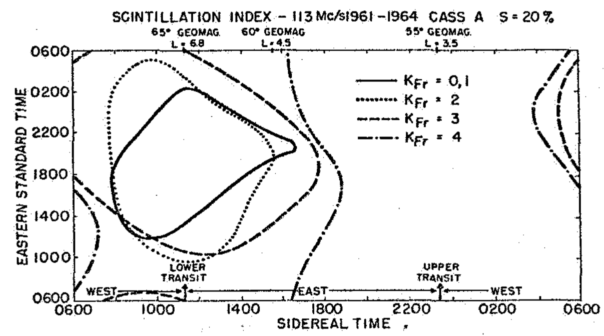

FIGURE 6. *20 percent contours of 113 Mc/s scintillation index.*
The irregularity region extends southwards toward upper transit with increasing K index. A magnetic disturbance produces the most effect in the early morning hours (0200–0800 EST) the least effect 1800–2200 EST.

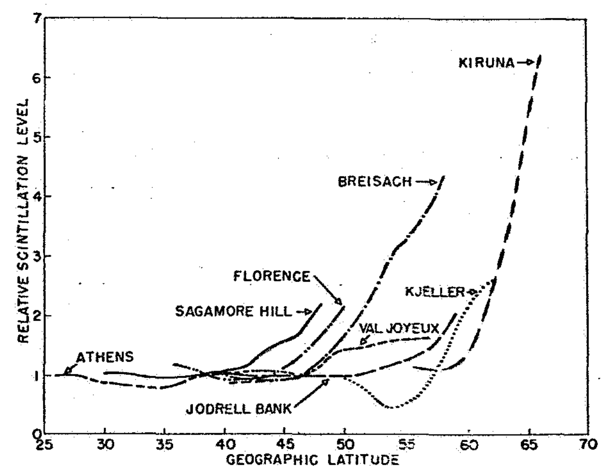

FIGURE 7. *Latitude variation of Transit 4A at 54 Mc/s as found by the Joint Satellite Studies Group (1965).*
Low indices at midlatitude observatories give evidence of a relatively undisturbed ionosphere; higher indices at subauroral latitudes indicate the existence of a latitude gradient in the irregularity structure.

index toward high latitudes and the lack of it at equ elevation angles to the south. While the radio st data, by itself, could not establish this conclusion, can now be used to examine it in greater detail.

In figure 8, the radio star observations have been ;parated according to level of magnetic activity. dereal values have been converted to spatial coordi- ıtes using the illustrative locus of figure 1. Transit \ scintillations observed at Sagamore Hill at 54 Mc/s ıring July 1961 to July 1962 have been scaled for ımparison with the 113 Mc/s radio star data. The :aling factor used was consistent with the observed equency dependence of the scintillation index at 63, .3, and 228 Mc/s for quiet magnetic conditions [Allen, arons, and Whitney, 1964].

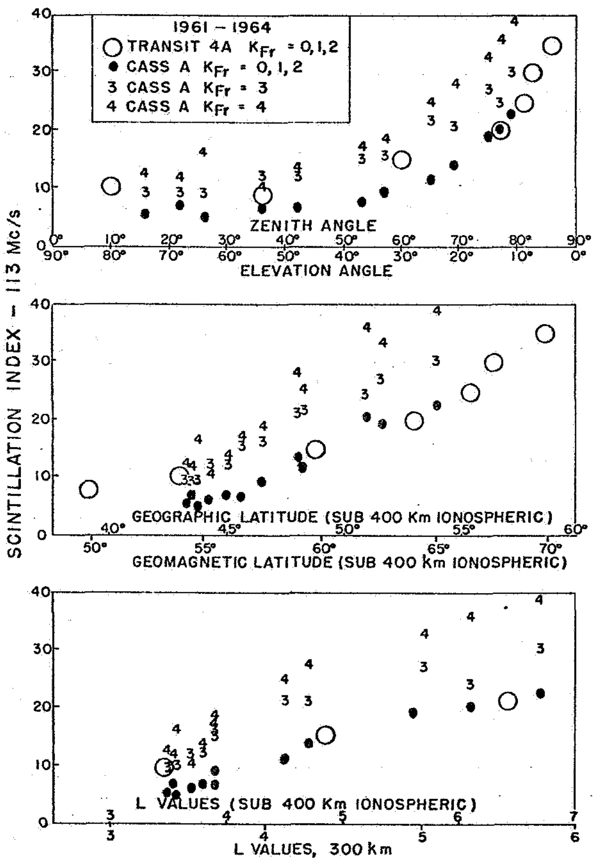

FIGURE 8. *Comparison of satellite scintillations with those of Cassiopeia.*

54 Mc/s observations of Transit 4A have been scaled for comparison at 113 Mc/s. Indices are plotted for both sets of data as a function of elevation angle, geomagnetic and geographic latitudes, and L values. It should be noted that the irreularity region moves southward and the scintillation index increases in mean value with increasing magnetic activity.

We believe that the radio star observations are con- ;tent with the model that has been advanced to plain the satellite observations. Under quiet mag- tic conditions, the mean frequency of occurrence d the intensity of the irregularities which produce intillation increase as the subauroral latitude of servation is increased. Further, as the magnetic tivity increases, the irregularity region moves south- ırd. Although there is presently insufficient data : conviction, it appears from the plot of scintillation lex versus L values (fig. 8) that during magnetic disturbances there is a greater proportionate increase in scintillation index at subauroral latitudes than at auroral latitudes. In any case, theories which would explain the irregularities in terms of local heating or local ionization due to precipitating particles must take into account the wide latitude range over which the irregularity structure is enhanced by magnetic disturbance.

5.2. East-West Asymmetry

Having found that the scintillation index does depend upon the state of magnetic activity, we might expect to find, as a consequence of the higher magnetic latitude on the western side, an indication of east-west asymmetry. Mawdsly (1960) proposed that there would be enhancement of scintillation when the ray path made a right angle intersection with thin irregularities aligned along magnetic field lines and that the scattering efficiency would be decreased with departure from this condition. A maximum of satellite scintillation to the west of north, centered close to the direction of the magnetic pole for his site, was reported by Lawrence, Alexander, Jr., and Martin, [1962]. Briggs and Parkin [1963] reject the proposal of Mawdsly except for sharply bounded irregularities. Their calculations for irregularities with slow changes of electron density near their boundaries suggest that the maximum of scintillation depth will occur when the irregularities are viewed "end on." Using an interferometer at 38 Mc/s in Cambridge, England, Briggs [1964] had failed to find a significant difference between east and west scintillation indices. The magnetic field is about 11° W in England. At the Sagamore Hill Radio Observatory, early observations had shown that satellite scintillations for conditions of low magnetic activity were greater in the direction of the magnetic field (315–360 azimuth sector) than in the corresponding sector (0–45° azimuth) to the east at equal angles of elevation [Joint Satellite Studies Group, 1965].

The mean of all of the observations would show only a slight skewness because of the strong bias for observations at the most frequent magnetic indices, $K_{Fr}=2$ and $K_{Fr}=3$. There is no evidence in favor of Mawdsly's proposal. Since the region through which the ray path is parallel to the magnetic field is just to the south of our station, the proposal of Briggs cannot be examined.

The detailed behavior displayed in the isopleths is quite complicated. To repeat, the purely geometric effect of elevation angle should appear as symmetry about lower and upper transit, the western direction of the magnetic field might skew the distribution of scintillation indices so that they are higher on the west. The isopleth for low magnetic activity (fig. 2, $K=0, 1$) shows an enhancement in the west during the time period 0600–1800 and a general symmetry for the period 1800–0600. This pattern changes with increasing magnetic activity. Comparing figure 3 with figure 4, we observe higher scintillations on the western side during the period 1800–0600 than on the east. This becomes more pronounced with increasing K index until in figure 5 the nighttime 40 percent contour is clearly isolated to the west.

On the other hand, the daytime (0600–1800) contours are skewed toward the east, becoming more pronounced with increasing K index until in figure 5 the nighttime 40 percent contour is situated to the east of lower culmination.

5.3. Spread *F* and Scintillations

It is important to try to understand the morphology of the scintillation irregularities in terms of the other well studied ionospheric irregularities: sporadic E and spread F. While sporadic E must produce marked diffractive effects, particularly in the HF and LF region of the radio spectrum, it cannot explain the general behavior displayed in the isopleths of scintillation index, because at mid and subauroral latitudes sporadic E is primarily a summer daytime phenomenon.

Briggs [1965] has correlated amplitude scintillations at 38 Mc/s with an index of spread F compiled from reexamined ionosonde records. His results supported a close association of scintillation and bottomside spread F during the minimum of the solar cycle and a lack of it during solar maximum. He proposed that the height of the irregularities producing spread F may be predominantly above the F region peak during solar maximum and, therefore, unobservable by bottomside ionosondes. We feel that the general findings in favor of the same or a closely related cause producing both the scintillation irregularities and the spread F irregularities justifies the use of reviews of spread F to attempt an understanding of the scintillation morphology.

5.4. Latitude Variation

In figures 9a and b, we have reproduced the curves of Calvert and Schmid [1964] which illustrate the percentage occurrence of spread F as obtained by both topside and bottomside sounders. At 1200 and 2400 EST, we have superimposed a bar over the geomagnetic latitudes (55°–65° N) covered by this study. At these subauroral latitudes nighttime occurrence of spread F is more frequent than daytime, but all times show a steadily increasing occurrence of spread F with increasing latitude. Similarly, both the frequency of occurrence and the index of radio star scintillation peak at nighttime and increase with increasing latitude. When comparing the details of these illustrations, it should be noted that, although both are for northern winter over 75° west longitude, the topside observations (fig. 9a) are near solar minimum, September 1962–January 1963, while the bottomside observations (fig. 9b) are for solar maximum (IGY). The local noon radio star and satellite scintillations have shown a steep gradient to the north, the

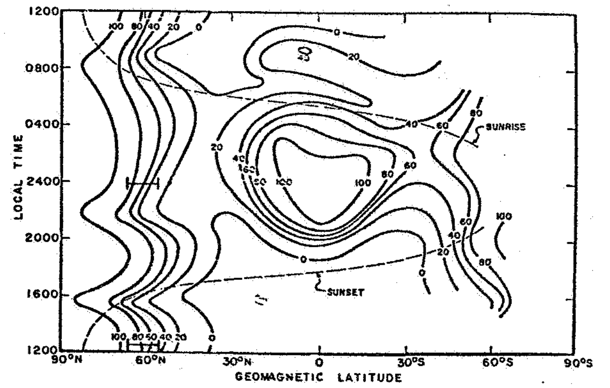

FIGURE 9a. *The percentage occurrence of aspect-sensitiv scattering observed by the Alouette topside sounder satellite.* Ground sunset and sunrise for the middle of the observation period, Nov. 1 1962, are noted [W. Calvert and C. W. Schmid, 1964]. Bars at 1200 and 240 are for 55°–65° geomagnetic north, the range covered in this study.

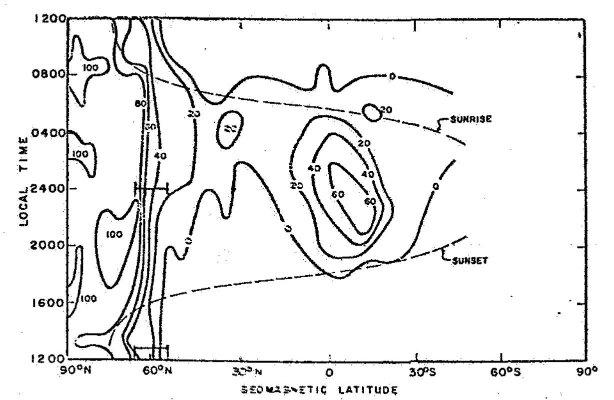

FIGURE 9b. *The percentage occurrence of frequency spread ing observed by ground-based ionosondes during the IG [W. Calvert and C. W. Schmid, 1964].*

index varying by a factor of about 20 in figures and 4.

Similar variation, emphasizing the steep nort gradient, is apparent in the satellite data (fig. 8). nearly concurrent topside observations do not sh comparable gradient in this time period, but bottomside IGY observations of figure 9b have a s gradient from zero to 40 percent occurrence w a short latitude interval. Near midnight both the side and bottomside latitude gradients of sprea are compatible with the latitude gradient of sci lation index. Note, however, that for both spre maps the peak occurrence is after midnight, whe the scintillation occurrence definitely peaks be local midnight at Sagamore Hill. Finally, the period 0200–0500 EST shows the lowest gradie spread F with latitude for both the top and bottom ionosoundings. This is in line with the similar havior of the radio star and satellite scintillation du this time period.

Certainly it is too early to decide on the role of the ɔside versus bottomside spread F in scintillation ıdies. At first glance, however, it seems that the me agent is evident at subauroral latitudes in both intillation and spread F.

The east-west asymmetry observed in the scintil-:ion isopleths for Sagamore Hill had two quite dif-rent features. First, for low magnetic activity $=0$ and 1), there is an enhancement to the west of ıgnetic north in the daytime and toward the east the nighttime. Second, for higher magnetic index $(=3, \geq 4)$ the opposite is observed.

This asymmetry may be partly explained by con-lering the auroral zone spread F model proposed Penndorf [1962]. Analyzing hourly IGY ionosonde ports he found a zone of maximum spread F that incided with the auroral zone. It has two prominent ıtures, a permanent maximum located in the Hudson ıy area over Foxe Basin and a traveling maximum th its center approximately at magnetic midnight the auroral zone. During the IGY the permanent ıximum had very littly diurnal, seasonal or magnetic index) variation.

Local daytime contours of spread F are dominated the permanent maximum. Penndorf's results licate that in our observational range the contours low lines of magnetic latitude, resulting in higher read F in the west during the daytime. The skewing the west can be observed in the 0600–1800 EST intillation contours at $K=0$, 1 and $K=2$. (The rsistent sharp northern gradient is evident in the ytime satellite results.)

During the night the traveling maximum appears the east and causes the spread F contours to skew stward despite the local magnetic field, while in the edawn period the spread F contours become sym-etrical. Scintillation indices appear to follow this me general behavior.

It should be noted that Penndorf has included data all K indices. He found no significant variation of e permanent maximum with magnetic activity, hough others [Shimazaki, 1962] have found positive rrelation for subauroral spread F. Perhaps during ıgnetic disturbances the irregularities producing read F are either masked by lower ionization or are edominately above the F region.

The scintillation observations for disturbed con-ions cannot be explained consistently with Penn-rf's model. The magnetic time of occurrence of e traveling maximum must be changed drastically account for the eastern enhancement during the rly daytime. For instance, for $K \geq 4$, the peak in intillations has moved to about 0900 local time.

It is interesting to note that Reid [1957] proposed a sic movement of the irregularity region at high lati-les. Examining the sidereal variation of the per-ntage occurrence of high scintillation rates, he found eak near lower transit for Ottawa observations but eak about one hour after lower transit for Saskatoon observations. From an informative analysis of the change of layer thickness with elevation angle and the effect of elongation of irregularities along the local magnetic field lines, he deduced a drift motion roughly at right angles to the horizontal component of the local magnetic field. Since perpendiculars to this drift motion at Ottawa and Saskatoon intersected near the dip pole, Reid proposed an average drift of the irregularities around that pole. Chivers [1960], observing at Jodrell Bank, found a similar asymmetry in scintillation rates but preferred to interpret it in terms of greater drift speeds at higher geomagnetic latitude.

Note that in our discussion, we have proposed that a disturbance is traveling about the North Polar region, perhaps the same disturbing force which is responsible for spread F, but that we cannot, from our index $\frac{\Delta P}{P}$, say anything about drift velocities of the irregularities. Our unpublished rate data, however, supports the observations of Reid in that there is a greater scintillation rate on the western side of lower transit in the direction of the local dip pole. An analysis of the rate observation is being prepared for future publication.

6. Summary

The strong diurnal variation, peaking about two hours before local solar and magnetic midnight, is still unexplained.

The sidereal variation is consistent with a sharp gradient in the occurrence of ionospheric irregularities at high latitudes.

A strong east-west asymmetry in quiet day data may be understood in terms of a time dependent irregularity structure similar to, if not the same as, the fixed and traveling spread F maxima found by Penndorf [1962]. It is proposed that the shift of the time of occurrence of peak scintillation activity to early daytime hours, for magnetically disturbed conditions, may reflect a change of the location of a traveling irregularity region from magnetic midnight to early morning hours.

7. References

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(Paper 1–10–

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Seasonal Variations in Occurrence of Scintillation

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Observations of scintillation on signals radiated on a frequency of 20.005 Mc/s from a series of satellites are used to derive diurnal variations in the appearance of scintillation. Marked seasonal changes in daytime scintillation are apparent, but it is shown that summarizing for the four conventional seasons may mask some of the more significant changes.

1. Introduction

This paper is a brief preliminary report on investigations in progress, with emphasis on seasonal changes; and more extensive analyses are being made. The local variations will be established more definitely when a full year's data from satellite BE–C are available, and latitude variations will be examined with the data now becoming available from a north-south chain of stations recording satellite S–66.

Comparisons with other phenomena and observations in the Northern Hemisphere are therefore being deferred until the more detailed analyses are completed.

In a previous paper by the author,[1] signals from the satellite Nora Alice I were analyzed to show the location and height of regions producing scintillation during October and early November, 1961. During that period scarcely any scintillation was apparent on the daytime records.

A similar satellite, NA II, was in orbit and tr mitting on the same frequency, 20.005 Mc/s, f December 14, 1961 to February 24, 1962. It found that results were then markedly different, s tillation being present in some degree on the g majority of daytime records.

Several satellites of the Cosmos series launchec the U.S.S.R. transmitted on the same frequency, gi a useful sequence of observations throughout the y and enabling clear seasonal changes in the diu variation of occurrence to be established. This formation has now been supplemented by almo complete year of observations of S–66, which provi very good confirmation of the seasonal patterns diurnal variation, and by observations from BE

2. Treatment of Data

Scintillation observed on signals passing thro the ionosphere shows great variations in depth quasi-period as well as in occurrence, and these r be affected by a number of factors which must corrected for, if accurate comparisons are desi

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